LCA Case Studies

Energy Aspects in LCA of Forest Products

Guidelines from Cost Action E9

Gerfried Jungmeier[1]*, Fred McDarby[2], Anders Evald[3], Catharina Hohenthal[4], Ann-Kristin Petersen[5], Hannes-Peter Schwaiger[1] and Bernhard Zimmer[6]

[1] Joanneum Research, Institute of Energy Research, Graz, Austria
[2] Enterprise Ireland, Environment Unit, Dublin, Ireland
[3] dk-Teknik, Soeborg, Denmark
[4] Kcl, Helsinki, Finland
[5] Agricultural University of Norway, Department of forest science, Aas, Norway
[6] Holztechnikum Kuchl, Kuchl, Austria

***Corresponding author:** Dipl-Ing. Dr. Gerfried Jungmeier, JOANNEUM RESEARCH ForschungsgmbH, Institute of Energy Research, Elisabethstrasse 5, A-8010 Graz, Austria (gerfried.jungmeier@joanneum.at)

DOI: http://dx.doi.org/10.1065/lca2002.08.096

Abstract

Intention and Background. This paper outlines guidelines for the treatment of energy in LCAs of forest products. The paper is a result of the Cost Action E 9 'Life cycle assessment of forestry and forest products' and reflects the experience of Cost E9 delegates, contributing to Working Group 'End of life – recycling, disposal and energy generation'.

Objectives. After overviewing different aspects of energy in LCA of forest products, the most important aspects are identified: 1) energy and carbon balance, 2) energy generation, 3) energy substitution and 4) comparison with other waste management options. For these aspects, guidelines are developed and examples are given to demonstrate the practical application of recommended guidelines.

Conclusions. Beside the proper treatment of the above mentioned aspects, the following conclusions for the LCA practitioners are given: 1) Draw attention to losses of potential energy in carbon flows. 2) Compared to heating value of biomass the auxiliary energy need is low (<10%). 3) The substitution rate (bioenergy for fossil fuel) might be lower than 100%, depending on technical systems available. 4) A high substitution rate might be an optimisation criterion for LCA. 5) A sensitivity analysis of different substitution criteria should be made. 6) Compare energy generation to other waste management options. 7) Use of bioenergy might be 'CO_2-neutral', but not 'CO_2-free'. 8) Most important benefit of bioenergy is greenhouse gas reduction by substituting fossil energy.

Keywords: Bioenergy; carbon balance; Cost Action E9; energy aspects; energy balance; energy generation; energy substitution; forest products; forestry; life cycle assessment; waste management; wooden products

Introduction

In general, it is accepted that energy aspects play a crucial role in LCA of forest products and the treatment of energy might have a significant influence on the results. That is why common rules seem to be necessary to harmonise different approaches for energy aspects.

This paper deals with guidelines for the treatment of energy in LCAs of forest products. The paper is a result of the Cost Action E 9 'Life cycle assessment of forestry and forest products' and reflects the experience of Cost E9 delegates, who contributed in the Working Group 'End of life – recycling, disposal and energy generation'.

Increasing the use of bioenergy is one promising option to reduce greenhouse gas emissions. The future use of bioenergy is influenced by technical, economic and ecological criteria like: costs of bioenergy, logistics of biofuel handling, auxiliary energy for fuel preparation, ash treatment, nutrient recycling, energy and carbon balance, technical developments in energy generation, substitution of conventional energy.

The following most important aspects for LCA practitioner are identified:

- aspects of energy and carbon balance,
- aspects of energy generation,
- aspects of energy substitution and
- aspects of comparison with other waste management options.

1 Energy and Carbon Balance

1.1 Guidelines

For a proper treatment of energy and carbon in LCA of forest products the following factors should be considered:

- characteristics of wood,
- energy balance,
- primary energy input,
- carbon balance,
- CO_2-uptake of forest ecosystems,
- CO_2-emissions from wood combustion,
- carbon storage in forest carbon pools (trees, litter, soil).

The chief characteristics of wood and wood-based products are carbon, energy and water or moisture content. These characteristics should be given for each (intermediate) wood-based product flow (e.g. round-wood, sawn wood, plywood, wood chips) in the LCA of forest products. These characteristics may only change in unit processes (e.g. debarking, drying).

An energy balance should be given for each unit process including the energy in the wood or wood-based products. All auxiliary energy inputs should be given as final energy carrier (e.g. heat, electricity, oil) and as primary energy input (e.g. coal, oil, gas, biomass).

When comparing the cumulative energy demand in LCA of forest products, it is important to distinguish between renewable primary energy carriers (e.g. biomass, water) and non-renewable primary energy carriers (e.g. coal, oil, gas), because this is important for the LCA interpretation. In LCA of forest products, the energy fixed in the wood 'biomass' should be the primary energy carrier and not the solar radiation that transforms solar energy in biomass.

A carbon balance should be outlined for each unit process involved in the LCA study, including material losses of wood (e.g. harvesting, transport, storage) that must be carefully calculated as a C or CO_2-loss. The natural oxidation (heterotrophic respiration) of the wood during storage of wood chips, for example, releases CO_2-emissions. The conversion from C into CO_2 is based on the weight of the molecules (C = 12, CO_2 = 12+32 = 44; C = 44/12 CO_2).

The CO_2-uptake (and/or carbon-uptake) of wood via photosynthesis must be included in LCA of forest products. In most cases, a dynamic uptake model is not adequate or applicable in LCA studies, therefore a simplified static approach to calculate the CO_2-uptake should be used, i.e. calculation of fixed carbon amount in wood taken out of the forest: 1 kg of wood with 50% water content amounts to 0.25 kg of carbon, so CO_2-uptake can be accounted as 0.9 kg of CO_2 removed from the atmosphere. The carbon uptake should be calculated in one of the unit processes related to forestry, but the assumed time scale for the carbon fixation must also be described in a simplified approach.

The CO_2-emissions from wood combustion must be calculated and included in the LCA for a proper illustration of the carbon balance, because the combustion of wood under a sustainable wood production is (might be) CO_2-neutral, but not CO_2-free. The calculation is done including water content, carbon content and heating value of the wood, i.e. the combustion of 1 kg wood (water content 20%, carbon-content 41%) leads to 1.5 $kgCO_2$, with lower heating value (13.1 MJ/kg) the CO_2-emission is 0.115 kg_{CO2}/MJ_{wood}.

The possible change of carbon storage pools in the forest (i.e. trees, soil and litter) by taking out wood from forest should be considered, at least as a qualitative description (Jungmeier [1] and Schlamadinger [2] outline further details). The most important carbon compartments in forest ecosystems are living vegetation (trees and ground vegetation), dead organic matter and the forest soil.

For the interpretation of the carbon cycle, it is important to consider the following aspects: assumed rotation period of forest ecosystem, change of carbon storage pools, landfill of wood-based waste and recycling. For an easier interpretation of carbon and CO_2 flows, it is advisable to distinguish between carbon from a biogenic (C_{bio}) source and carbon from fossil origins (C_{fos}).

Energy generation avoids natural oxidation (respiration) of biomass by emitting the same amount of CO_2, therefore the carbon cycle might be closed. The closure of the carbon cycle strongly depends on the rotation period taken under consideration, because the heterotrophic respiration of dead organic matter takes about 30 to 50 years to release the carbon, whereas the combustion for energy generation causes releases of this stored carbon at once.

1.2 Examples

In **Fig. 1**, the energy balance of heat from a district heating plant fired with wood chips is outlined for each analysed unit process referring to 1 kWh of heat supplied to the consumer. The energy uptake during forest growth is calculated in the unit process 'collection', this energy is fixed in the wood until the wood chips are burned in the heating plant. During storage the wood chips are dried in the sun and natural ventilation (water content reduction), which leads to an increase of the heating value. The material losses of wood chips during chipping and transportation are calculated as energy losses, because a natural decomposition of these losses over time is assumed. In the heating plant, the energy fixed in wood chips is converted into hot water that is distributed for space heating in a district-heating network.

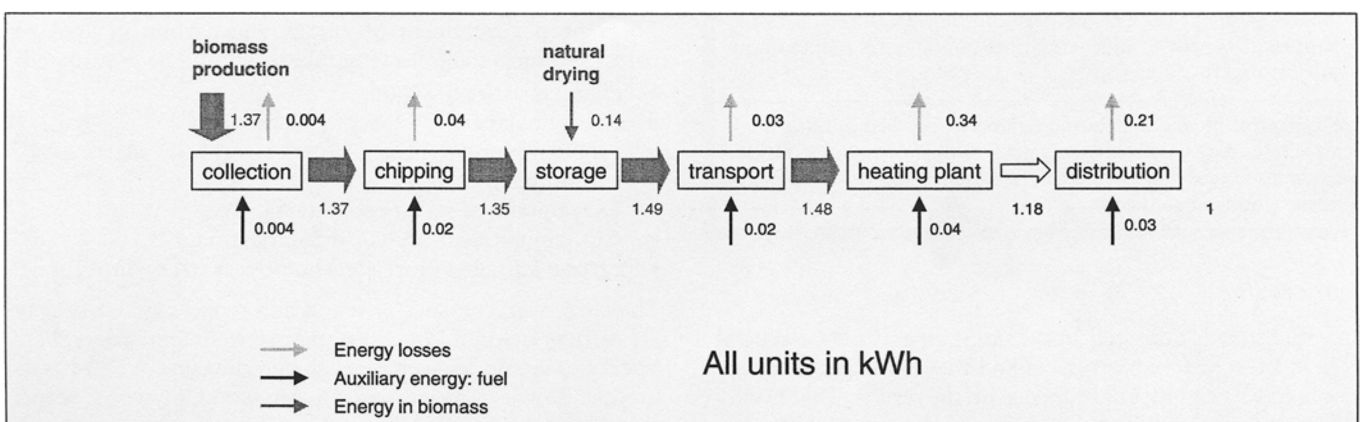

Fig. 1: Energy balance of LCA of bioenergy – Example: heat from district heating plant fired with wood chips taken from Jungmeier [3]

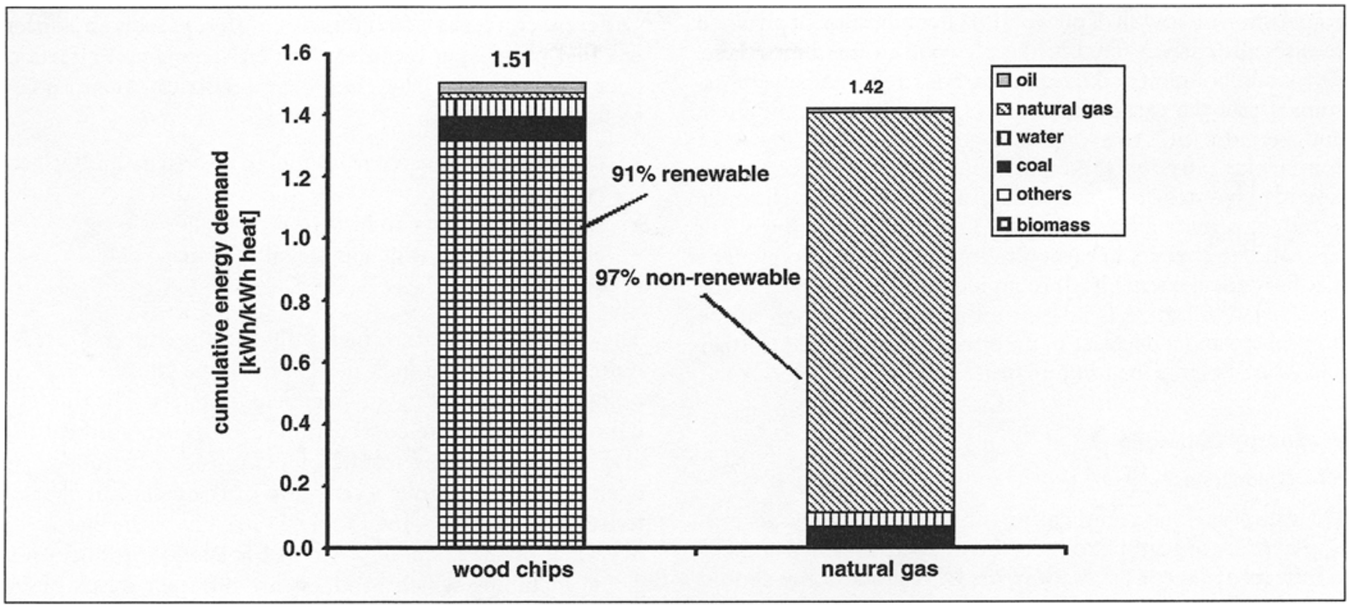

Fig. 2: Cumulative energy demand in LCA of bioenergy – Example: comparison heat from district heating plant fired with wood chips and with natural gas, data derived from Jungmeier [3]

In **Fig. 2**, the cumulative energy demand of 1 kWh heat from a district heating plant with wood chips is compared to a district heating plant with natural gas. The cumulative energy demand of the wood chip plant is a little higher than the natural gas, mainly because of the lower conversion efficiency in the heating plant. The primary energy of the wood chips is biomass. The main part of the primary energy of the wood chip system is biomass, which means that 91% of the primary energy is from renewable energy resources. The main part of the primary energy of the natural gas system is natural gas, which means that 97% of the primary energy is from non-renewable energy resources. Comparing the non-renewable energy resources, the biomass system has 'only' 0.14 kWh/kWh_{heat} compared to 1.38 kWh/kWh_{heat} from the natural gas system.

In **Fig. 3**, the carbon balance of a plywood life cycle is outlined for each analysed unit process. The carbon balance describes the carbon flows between the technical system and the atmosphere and the lithosphere. The carbon uptake during forest growth is calculated in the unit process 'cultivation', this carbon is fixed and stored in the wood. The material losses during harvesting and transport are shown as carbon flows to the atmosphere assuming a heterotrophic respiration. The wood waste out of the 'fabrication' process is calculated as carbon flow to atmosphere. Parts of this wood waste are used for energy production for the fabrication and the rest is used for other material purposes like particle board, assuming that - sooner or later - this carbon will also be released to the atmosphere. The carbon in fossil fuels is taken from the lithosphere. For the end of life, two possibilities are shown:

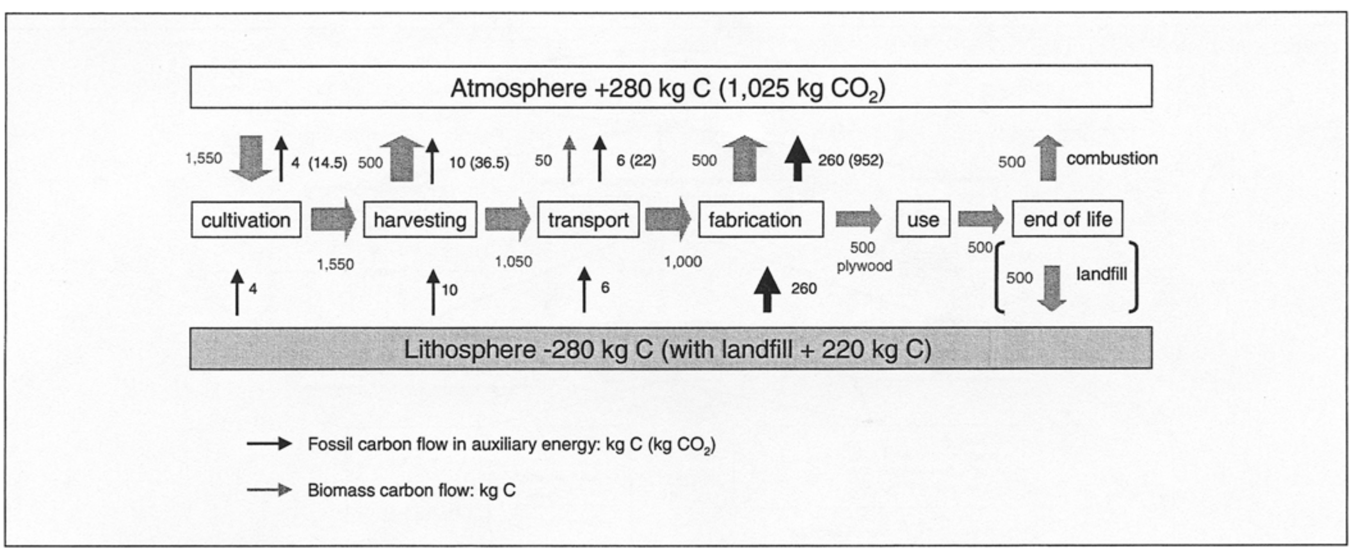

Fig. 3: Carbon balance of LCA of wooden product – Example: plywood, data derived from Gemis [4]

combustion or landfill of plywood. The combustion of plywood releases the carbon fixed in the plywood to the atmosphere. The landfill of plywood fixes the carbon in the lithosphere, assuming that the carbon in plywood will not be decomposed, and therefore leads to a long-term storage of carbon. In case of combustion purposes at the end of life, the sum of carbon flows related to biomass from and to the atmosphere over the lifecycle is zero, assuming a time of about 80 years for the growing of trees and no changes in carbon storage pools in the forest. The auxiliary fossil energy leads to an increase of 280 kg C. In the case of landfill there is at least an increase of carbon in the lithosphere and a decrease in the atmosphere assumed (further details are documented in Jungmeier [1,3].

2 Energy Generation

2.1 Guidelines

There are various technical possibilities of energy generation in LCA of forest products. To analyse the environmental effects of energy generation, the LCA practitioner should consider the major aspects of

- conversion technology,
- fuel, and
- fuel processing.

Different conversion technologies, different fuels and different fuel processing bring varying environmental effects of energy generation. The chief characteristics of conversion technologies are:

- conversion efficiency from fuel to electricity and/or heat (η_{el}, η_{th}),
- ratio of electricity to heat ($\alpha = \eta_{el}/\eta_{th}$),
- emissions to air (flue gas cleaning system) and
- ash treatment.

The characteristics of the fuels influence the conversion technology and different fuels used in the same conversion technology lead to varying environmental effects. The processing of the fuel before combustion (e.g. drying, gasification) also might affect the results of LCA studies seriously. An example for a possible description of the technical characteristics of a CHP plant (**Table 1**) are given. In **Fig. 4**, an overview of the systems of wood for energy production is given, including which products are different forms of energy like heat, electricity (and heat in combined heat and power plants) and liquid fuels.

Table 1: Technical characteristics of the CHP Plant Reuthe, further details see in Mathis [5] and Jungmeier [6]

Annual production (normal year)	District heat	29 GWh
	Grid electricity	4.7 GWh
Boiler	Steam mass flow	10 t/h
	Steam temperature	445°C
	Steam pressure	32 bar
Fuel	Composition	No bark, but partially water with glue, 5% wood powder, 30% sawdust, 65% shavings
	Moisture content	8 to 12% dry
	Lower heating value	4.5 to 4.8 kWh/kg
Turbine	Type	Counterpressure turbine
	Electric power	1.265 MW
Flue gas	Particle separator	Multicyclone with electrostatic filter
	Flue gas volume flow	17 000 Nm^3/h (13% O_2)
	Flue gas temperature	170°C

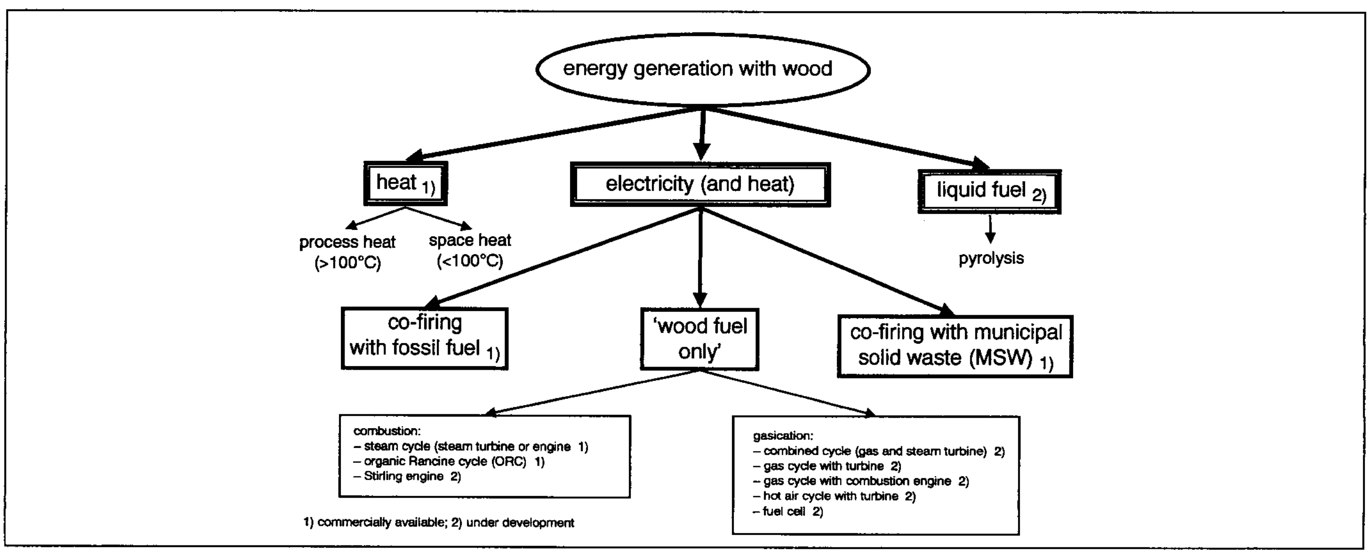

Fig. 4: Overview of systems for energy generation from wood

2.2 Examples

The influences of the conversion technology, of the fuel and the fuel processing on results in LCA are illustrated by examples for the greenhouse gas emissions.

Influence of conversion technology – combined heat and electricity production with wood chips

- steam turbine 33 g CO_2-eq./(0.33_{el} + 0.67_{th}) kWh and
- hot air turbine 80 g CO_2-eq./(0.33_{el} + 0.67_{th}) kWh, further details see in Jungmeier [3].

Influence of fuel - heat supply with a central heating system fired with

- wood briquette 25 g CO_2-eq./kWh and
- wood pellet 37 g CO_2-eq./kWh.

Influence of fuel processing - heat supply with a central heating system fired with

- pyrolysis oil from wood chips 60 g CO_2-eq./kWh and
- wood gas from fluidised bed gasification of wood chips 100 g CO_2-eq./kWh.

3 Energy Substitution

3.1 Guidelines

In LCA of forest products, energy generation from wood (bioenergy) might substitute fossil energy. It is a continuous debate among LCA-practitioners, which energy sources are substituted when wood is used for bioenergy. In addition to the goal and scope definition of the specific LCA study, the treatment of substitution is dependent on the following criteria that must be considered as documented in Jungmeier [7]:

- kind of energy output (e.g. fuel, electricity, heat, electricity and heat)
- quality of energy output (e.g. temperature, voltage, ratio between electricity and heat)
- energy supply/demand characteristic (e.g. base load, peak load, summer, winter, distribution, additional energy supply)
- state of technology (e.g. average substitutes average, new/old, new/new, new/average)
- kind of fossil fuel substituted (e.g. coal, lignite, natural gas, oil)
- costs (e.g. low substitutes high, high/high, medium/high, high/low)
- socio-economic and other factors (e.g. available potential, market conditions, employment, tradition, comfort of fuel handling)

There are also relevant interactions between these criteria, e.g. costs may limit the realisation of the fossil energy substitution or the introduction of new technologies may influence the employment. The consideration of these criteria for the substitution might lead to a substitution rate of sometimes less than 100%, e.g. 1 kWh of heat from bioenergy substitutes 0.9 kWh of heat from fossil energy.

4 Comparison with Other Waste Management Options

4.1 Guidelines

The comparison of different waste management options has been discussed controversially in the last decade among LCA experts. The combustion with energy generation of waste wood, waste paper and waste particle boards is compared to recycling of fibres (for particle board and/or paper) and landfill.

This comparison might become quite complex, because different waste management options supply different products, e.g. energy generation supplies energy, recycling supplies fibres and landfill is only for final disposal. Therefore, the choice of the adequate functional unit plays a crucial role in comparisons of energy generation to other waste management options. Depending on the goal and the scope definition of the LCA study under consideration, the two following different functional units are used for these comparisons in LCA of wooden products:

1. input-related functional unit without secondary products, e.g. treatment 1 t of waste wood and
2. input and output-related functional unit, e.g. treatment of 1 t of waste and supply of x kWh energy and y t fibres.

The input-related functional unit considers only the final disposal of a certain amount of waste wood as the practical value in the LCA and does not care about additional values like the supply of energy or fibres with their related possible benefits. The best environmental waste management option is defined as the option which has the lowest impacts from getting rid of a certain amount of waste, ignoring further benefits. Thus, the results, for example, refer only to the environmental effects of treating 1 t of waste wood (**Fig. 5**).

The input and output-related functional unit takes the additional benefits of a waste treatment option under consideration, i.e. on one hand waste wood is treated and on the other hand new products – energy and fibres – are supplied and might be used for further purposes. For the comparison of energy generation with recycling or landfill, this means that further systems for energy and fibre from any other resource than waste wood supply must be taken into account (Fig. 5). The input and output-related functional unit for comparison is defined in the following procedure: Beside the input of waste wood, the output of energy in the functional unit (e.g. x kWh) is determined by the energy generation and the output of fibres in the functional unit (e.g. y t) is determined by recycling. With this defined input and output-related functional unit, three systems are considered that provide the same functional unit: '1 t waste wood treated + x kWh energy + x t fibres'. These systems are

- system 1: landfill of waste wood with energy generation and fibre acquisition from any other resources
- system 2: recycling of waste wood with energy generation from any other resources
- system 3: energy generation of waste wood with fibre acquisition from any other resource

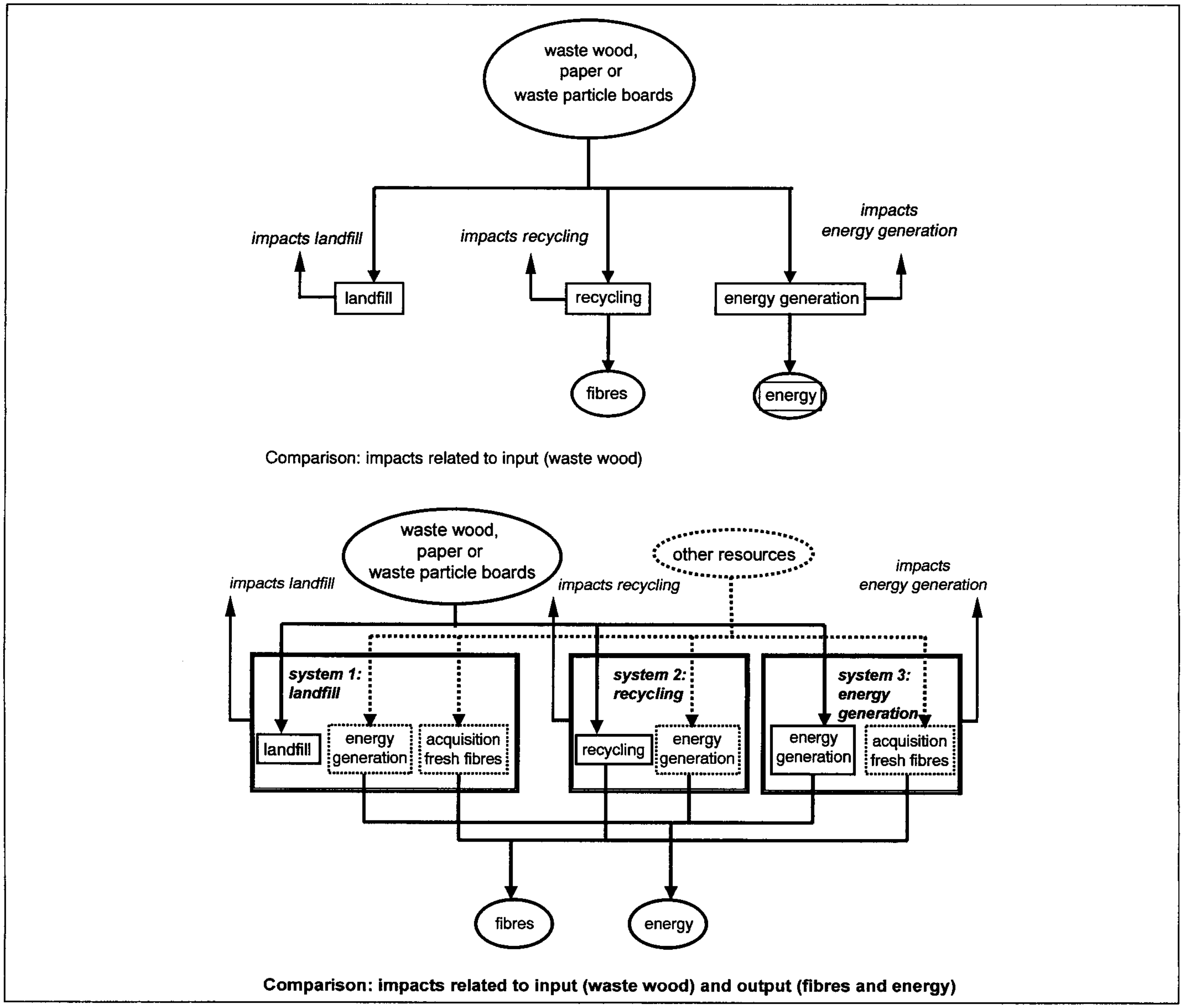

Fig. 5: Input-related functional unit for comparison of energy generation to other waste management options (above) in comparison to input and output-related functional unit for comparison of energy generation to other waste management options

4.2 Examples

An intensive fibre recycling is compared with combustion of fibre for energy generation using an LCA. In Pajula [8], the functional unit is 1 t of paper and board end product going to the consumer. It is assumed that all chemical pulp needed in German paper production is imported from Finland. In the reference case, 40% of all paper and board used by consumers is recovered. The case 'intensive fibre recycling' represents a situation in which the recycled fibre content of paper in Germany has been raised as high as possible with present technology (recovery rate 53%) and without any serious effect on quality. In the case 'energy generation' 40% is used for combined heat and power production, whereas the recovery rate is 53%. The results are shown in **Fig. 6**. Recycling results in less wood raw material (pulpwood from forestry) and lower emissions to water and air from wood harvesting and transport. Energy generation lowers the CO_2 and SO_2 emissions resulting from energy production. Recycling and energy production reduces the load on landfill sites and thus CH_4, COD and NO_x emissions are reduced.

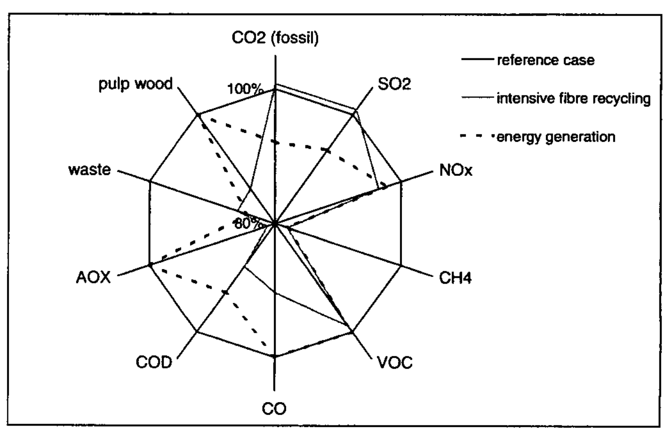

Fig. 6: Comparison of recycling and energy generation of fibres in Germany, data taken from Pajula [8]

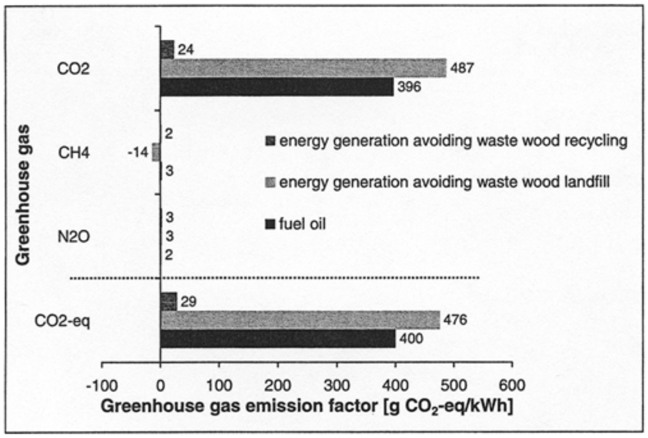

Fig. 7: Comparison of greenhouse gas emissions of energy generation from waste wood by avoiding recycling or landfill, basic data taken from Jungmeier [3]

A comparison of the greenhouse gas emissions of energy generation from waste wood to fuel oil is made considering the avoided reference use of the wood; recycling in particle board industry and landfill. In case of recycling, it is assumed that fresh fibres have to be taken from forestry to satisfy the current fibre demand of the particleboard industry and these emissions are allocated to the energy generation system. The results are shown in **Fig. 7**. The greenhouse gas emissions of energy generation are 476 g CO_2-equivalent per kWh of heat by avoiding landfill and are 17 times higher than avoiding recycling to particle boards with 29 g CO_2-eq/kWh. The greenhouse gas emissions of fuel oil are 400 g CO_2-eq/kWh. Avoiding of landfill of waste wood leads to a reduction of CH_4-emissions from landfill, but the carbon stored in landfill is emitted to air by combustion for energy generation, whereas the acquisition of fresh fibres has no significant additional greenhouse gas emissions. The input and output-related functional unit is the supply of 1 kWh of heat and of 0.25 kg fibres (assumption: efficiency heat generation 75%, efficiency recycling 80%, heating value 4.5 kWh/kg) with an input of 0.3 kg waste wood. For the results referring to 1 kWh heat only, the emissions from the supply of 0.25 kg fresh fibre acquisition are considered in the energy generation by substitution approach.

5 Conclusions

Summing up for the treatment of energy in LCA of forest products, the most important aspects are about energy and carbon balance, energy generation, energy substitution and comparison with other waste management options. In addition to these aspects, the following conclusions for the LCA practitioner are drawn:

- Draw attention to losses of potential energy (fibres, carbon) in carbon flows.
- Compared to heating value of biomass the auxiliary energy need is low (<10%).
- Upstream energy losses are low compared with heating value of the fuel/product (typically 1–10%).
- The substitution rate of bioenergy for fossil fuel might be lower than 100%, depending on technical systems available.
- A high substitution rate might be an optimisation criteria for LCA.
- A sensitivity analysis of different substitution criteria should be made.
- Compare energy generation to other waste management options.
- Use of bioenergy might be 'CO_2-neutral', but not 'CO_2-free'.
- Most important benefit of bioenergy is greenhouse gas reduction by substituting fossil energy.

Acknowledgement to the national funding by the Federal Ministry of Agriculture, Forestry, Environment and Water Management, Vienna, Austria.

References

[1] Jungmeier G, Schwaiger H (2001): Changing Carbon Storage Pools in LCA of Bioenergy – A Static Approach for a Dynamic Effect published in Life cycle assessment of forestry and forest products, ISBN 92-894-1292-5, Belgium 2001

[2] Schlamadinger B, Apps M, Bohlin F, Gustavsson L, Jungmeier G, Marland G, Pingoud K, Savolainen I (1997): Towards a Standard Methodology for Greenhouse Gas Balances of Bioenergy Systems in Comparison with Fossil Energy Systems, Biomass and Bioenergy Vol 13, No 6, 1997

[3] Jungmeier G, Canella L, Spitzer J, Stiglbrunner R (1999): Treibhausgasbilanz der Bioenergie – Ein Vergleich der Treibhausgas-Emissionen von Bioenergie-Systemen und fossilen Energiesystemen; (Greenhouse Gas Balance of Bioenergy – A Comparison of Greenhouse Gas Emissions of Bioenergy Systems and Fossil Energy Systems), Institute of Energy Research, Joanneum Research, Graz September 1999

[4] Gemis (2001): Global Emission Modelling of Integrated Systems, free available from http://www.oeko.de/service/gemis, Öko-Institut Darmstadt, Darmstadt, Germany 2001

[5] Mathis R (1996): Bau und Betrieb einer biomassebefeuerten Wärme-Kraft-Kopplung (Construction and Operation of a Biomass CHP Plant), Elektrotechnik und Informationstechnik 9, pp 616–623

[6] Jungmeier G, Resch G, Spitzer J (1998): Environmental Burdens over the entire Life Cycle of a Biomass CHP plant, Biomass and Bioenergy Vol 15, Nos 4/5, 1998

[7] Jungmeier G, Schwaiger H, Spitzer J (1998): The Treatment of Fossil Energy Substitution in LCA for Forest Products – Criteria and Case Studies, published in proceedings of Cost E9 Workshop Life Cycle Assessment of Forestry and Forest Products, 14–16 September 1998

[8] Pajula T, Kärnä A (1998): Life Cycle Scenarios of Paper, published in proceedings of Cost E9 Workshop Life Cycle Assessment of Forestry and Forest Products, 14–16 September 1998

Received: July 30th, 2001
Accepted: August 17th, 2002
OnlineFirst: August 20th, 2002